CHAPTER 3

The Mysterious Titan

The exploration of Titan is at the very heart of the Cassini–Huygens mission. As one of the primary scientific interests of the joint NASA–ESA mission, Titan is the sole focus of the Huygens Probe and one of the main targets of the Cassini Orbiter. Through the combined findings from Earth-based telescopes and the Voyager spacecraft, Titan has been revealed to be a complicated world, more similar to a terrestrial planet than a typical outer-planet moon.

A Smoggy Satellite

With a thick, nitrogen-rich atmosphere, possible oceans and a tar-like soil, Titan is thought to harbor organic compounds that may be important in the chain of chemistry that led to life on Earth.

Titan was discovered by Christiaan Huygens about 45 years after Galileo discovered the four large moons of Jupiter. In the early 1900s, the astronomer Comas Sola reported markings that he interpreted as atmospheric clouds. Titan's atmosphere was confirmed in 1944, when Gerard Kuiper passed the sunlight reflecting off Titan through a spectrometer and discovered the presence of methane.

Later observations by the Voyager spacecraft showed that nitrogen was the major constituent of the atmosphere, as on Earth, and established the presence of gaseous methane in concentrations of several percent. The methane participates in sunshine-driven chemistry, which has produced a photochemical smog.

Due to Titan's thick natural smog, Voyager could not see the surface, and instead the images of Titan's disk showed a featureless orange face.

This spectacular view of the edge of Titan was taken by Voyager 1 from a distance of 22,000 kilometers. Tenuous high-altitude haze layers (blue) are visible above the opaque red clouds. The highest of these haze layers is about 500 kilometers above the main cloud deck, and 700 kilometers above Titan's surface.

Spectroscopic observations by Voyager's infrared spectrometer revealed traces of ethane, propane, acetylene and other organic molecules in addition to methane. These organic compounds, known as hydrocarbons, are produced by the interaction of solar ultraviolet light and electrons from Saturn's fast-rotating magnetosphere striking Titan's atmosphere.

Hydrocarbons produced in the atmosphere eventually condense out and rain down on the surface; so Titan may have lakes of ethane and methane, perhaps enclosed in the round bowls of impact craters. Alternatively, liquid ethane and methane may exist in subsurface reservoirs. Titan's hidden surface may have exotic features: mountains sculpted by hydrocarbon rain, rivers, lakes and "waterfalls." Water and ammonia magma from Titan's interior may occasionally erupt, spreading across the surface and creating extraordinary landscapes.

The Cassini–Huygens study of Titan will provide a huge step forward in our understanding of this haze-covered world, and is expected to yield fundamental information on the processes that led to the origin of life on Earth.

By combining the results from the Cassini–Huygens mission with Earth-based astronomical observations, laboratory experiments and computer modeling, scientists hope to answer basic questions regarding the origin and evolution of Titan's atmosphere, the nature of the surface and the structure of its interior. Earth's atmosphere has been significantly altered by the emergence of life. By studying Titan's atmosphere, scientists hope to learn what Earth's atmosphere was like before biological activity began.

The investigation of Titan is divided into inquiries from traditional planetary science disciplines: What is its magnetic environment, what is the atmosphere like, what geological processes are active on the surface and what is the state of its interior? In this chapter, we describe how our knowledge of Titan has developed over the years, focusing on the primary areas of Titan science that the Cassini–Huygens mission will address. The final section discusses how Huygens' and Cassini's instruments will be employed to address fundamental questions, such as: What is the nature of Titan's surface, how have the atmosphere and surface evolved through time and how far has prebiotic chemistry proceeded on Titan?

CASSINI SCIENCE OBJECTIVES AT TITAN

- Determine the abundance of atmospheric constituents (including any noble gases); establish isotope ratios for abundant elements; and constrain scenarios of the formation and evolution of Titan and its atmosphere.
- Observe the vertical and horizontal distributions of trace gases; search for more complex organic molecules; investigate energy sources for atmospheric chemistry; model the photochemistry of the stratosphere; and study the formation and composition of aerosols.
- Measure the winds and global temperatures; investigate cloud physics, general circulation and seasonal effects in Titan's atmosphere; and search for lightning discharges.
- Determine the physical state, topography and composition of the surface; infer the internal structure of the satellite.
- Investigate the upper atmosphere, its ionization and its role as a source of neutral and ionized material for the magnetosphere of Saturn.

Saturn's Magnetosphere

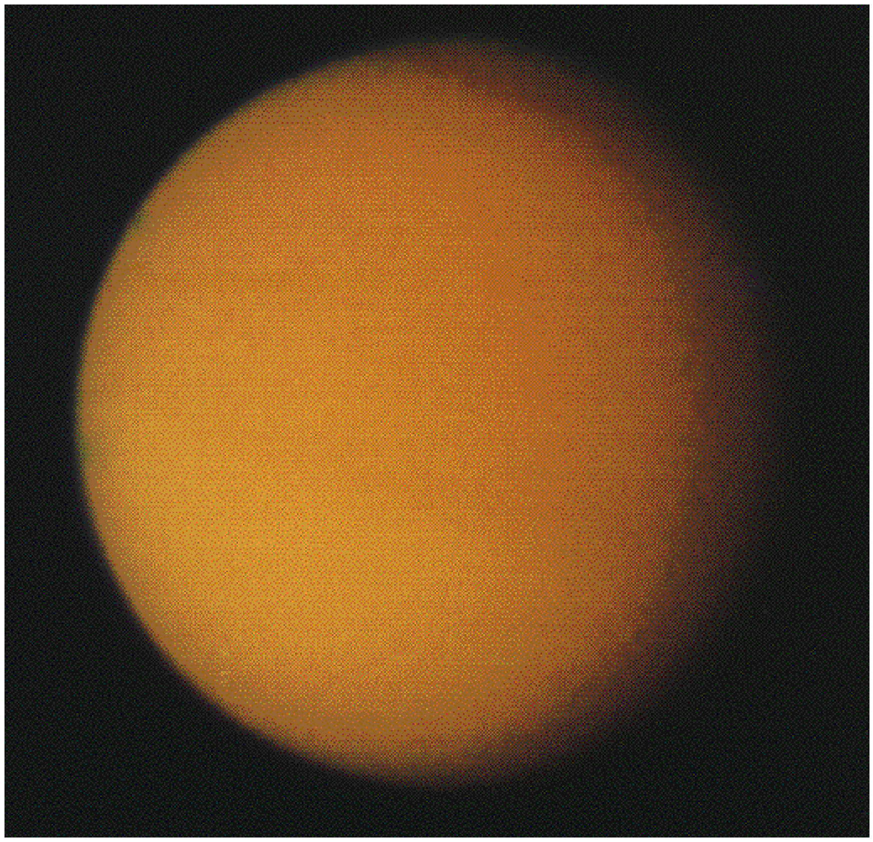
Saturn's magnetic field rotates with the planet, carrying with it a vast population of charged particles called a plasma. (Further discussion of Saturn's magnetosphere can be found in Chapter 6.) The interaction of Saturn's magnetosphere with Titan can be explained by the deflection of Saturn's magnetic field and the ionization and collision of Titan's atmosphere with the charged particles trapped in Saturn's magnetosphere. During the Voyager 1 flyby of Titan, clear indications of changes were observed in the magnetosphere due to the presence of Titan. The signatures included both plasma and plasma-wave effects, along with a draping of Saturn's magnetic field around Titan.

Titan in Saturn's Magnetosphere. Titan orbits Saturn at a distance of about 20.3 R_S (R_S = one Saturn radius). The conditions of the plasma environment in which Titan is submerged can vary substantially, because Titan is sometimes located in the magnetosphere of Saturn and sometimes out in the solar wind. Additionally, the angle between the incident flow and the solar irradiation varies during Titan's orbit. During the Voyager 1 encounter, Titan was found to be within Saturn's magnetosphere and the interaction was described as a transonic flow of plasma (above the local speed of sound).

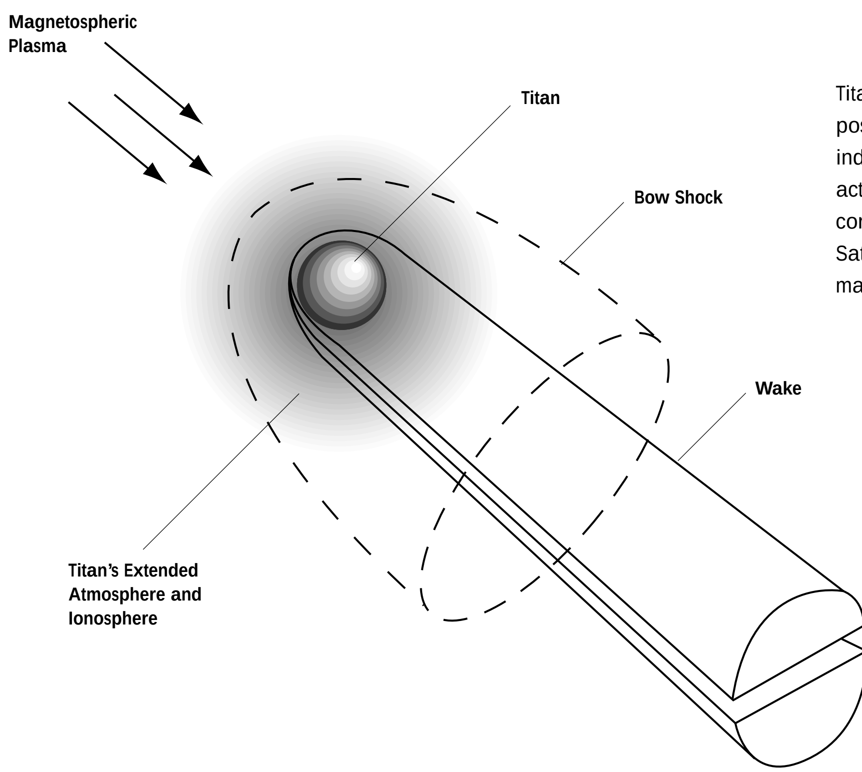
Scientists expect the characteristics of the incident flow to vary substantially depending on the location of Titan with respect to Saturn's magnetosphere. When Titan is exposed to the solar wind, the interaction may be similar to that of other bodies in the solar system such as Mars, Venus or comets (these bodies have substantial interaction with the solar wind, and, like Titan, have atmospheres but no strong internal magnetic fields).

Titan's Wake. The magnetospheric plasma flowing into and around Titan produces a wake. As with the Galilean satellites at Jupiter, the fast, corotating plasma of Saturn's magnetosphere smashes into Titan from behind, producing a wake that is dragged out in front of the satellite. The process is similar to one in which a wake is created behind a motor boat speeding through the water.

In this analogy, Titan is the motor boat and Saturn's magnetosphere is the water. Instead of the boat going through the water, the water is rushing past the boat. Titan is moving also, in the same direction as Saturn's magnetosphere, but slower, so the magnetospheric plasma actually pushes the wake out in front of the satellite. Scientists expect the wake to be a mixture of plasma from Titan and Saturn's magnetosphere. The wake may be a source of plasma for Saturn's magnetosphere, producing a torus of nitrogen and other elements abundant in Titan's atmosphere.



Exploring Titan is like investigating a full-fledged planet. With a radius of 2575 kilometers, Titan is Saturn's largest moon — larger than the planets Mercury and Pluto. Titan is the second largest moon in the solar system, surpassed only by Jupiter's Ganymede. This Voyager image of Titan shows the asymmetry in brightness between the moon's southern and northern hemispheres. Titan's natural smoggy haze blocked Voyager's view of the surface.



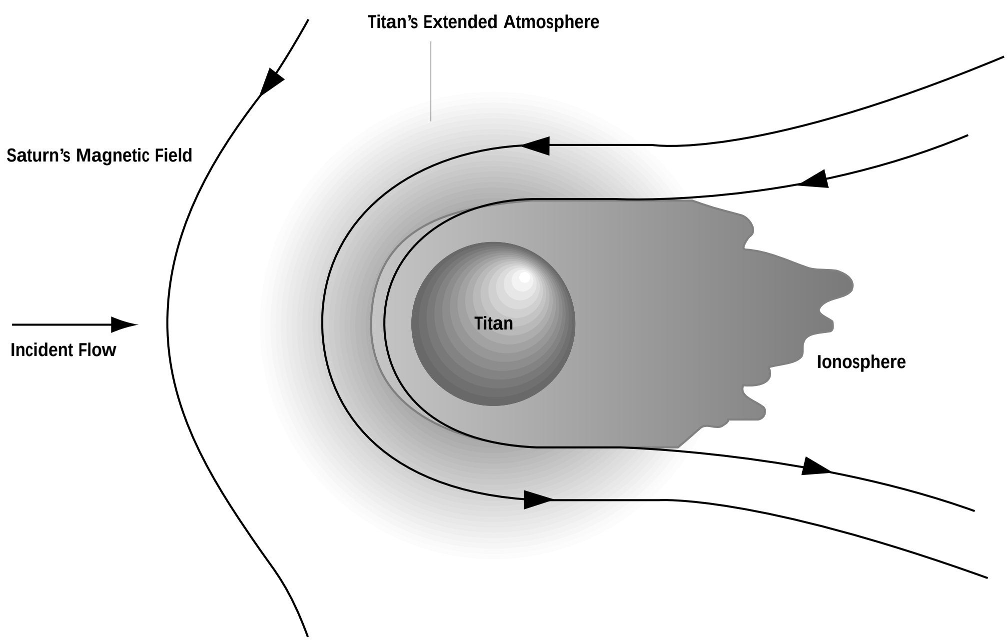
Titan's wake and the possible bow shock induced by the interaction of Titan with corotating plasma in Saturn's vast magnetosphere.

Titan's Torus. The interaction of Titan with Saturn's magnetosphere provides a mechanism for both the magnetospheric plasma to enter Titan's atmosphere and for the atmospheric particles to escape Titan. Voyager results suggested that the interaction produces a torus of neutral particles encircling Saturn, making Titan a potentially important source of plasma to Saturn's magnetosphere. The characteristics of this torus are yet to be explored and will be addressed by the Cassini Orbiter. The interaction of ice particles and dust from Saturn's rings will play a special role as the dust moves out toward Titan's torus and becomes charged by collisions. When the dust is charged, it behaves partially like a neutral particle orbiting Titan, according to Kepler's laws (gravity driven), and partially like a charged particle moving with Saturn's magnetosphere. The interaction of dust with Saturn's magnetosphere will provide scientists with a detailed look at how dust and plasma interact.

Atmosphere–Magnetosphere Interaction. Saturn's magnetospheric plasma, which is trapped in the planet's strong magnetic field, corotates with Saturn, resulting in the plasma flowing into Titan's back side. The flow picks up ions created by the ionization of neutrals from Titan's exosphere and is slowed down while the magnetic field wraps around the satellite. The characteristics of the incident flow are important because the incoming plasma is a substantial source of atmospheric ionization that triggers the creation of organic molecules in Titan's atmosphere. Thus, the aeronomy (study of the physics of atmospheres) of the upper atmosphere and ionosphere is dependent on the plasma flow and the solar radiation as a source of energy. Scientists expect that heavy hydrocarbons are the dominant ions in Titan's ionosphere.

Lightning on Titan? The extensive atmosphere of Titan may host Earth-like electrical storms and lightning. Although no evidence of lightning on Titan has been observed, the Cassini–Huygens mission provides the opportunity to determine whether such lightning exists. In addition to the visual search for lightning, the study of plasma waves in the vicinity of Titan may offer another method. Lightning discharges a broad band of electromagnetic emission, part of which can propagate along magnetic field lines as whistler-mode emission. The emissions are known as "whistlers" because, as detected by radio and plasma-wave instruments, they

The flow of charged particles in Saturn's magnetosphere past Titan is slowed by the ions created from collisions with Titan's extended atmosphere. Saturn's magnetic field becomes draped around Titan.



SIX GIANT SATELLITES

Satellite (Planet)	Titan (Saturn)	Moon (Earth)	Io (Jupiter)	Europa (Jupiter)	Ganymede (Jupiter)	Callisto (Jupiter)
Distance from Parent, kilometers	1,221,850	384,400	421,600	670,900	1,070,000	1,883,000
Rotation Period, days	15.945	27.322	1.769	3.551	7.155	16.689
Radius, kilometers	2575	1738	1815	1569	2631	2400
Average Density, grams per cubic centimeter	1.88	3.34	3.57	2.97	1.94	1.86

have a signature of a tone decreasing with time (because the high frequencies arrive before the low frequencies). Lightning whistlers have been detected in both the Earth and Jupiter magnetospheres and, besides being detectable from large distances, they offer an opportunity to estimate the frequency of lightning flashes.

Titan's Magnetic Field. The question of whether or not Titan has an internal magnetic field remains open, although Voyager results did not suggest the presence of one. Recent Galileo results from Jupiter indicate the possibility of a magnetic field associated with the moon Ganymede. For Titan there are two possibilities — a magnetic field could be induced from the interaction of Titan's substantial atmosphere with the flow of Saturn's magnetosphere (such as at Venus, with the solar wind), or a magnetic field could be generated internally from dynamo action in a metallic molten core (such as at Earth).

In addition to being important to understanding the Titan interaction with Saturn's magnetosphere, a Titan magnetic field, if generated internally, would place strong constraints on its interior structure.

Titan's Atmosphere

Background. The discovery of methane absorption bands in Titan's spectrum in 1944 was the first confirmation that Titan has an atmosphere. Theoretical analysis followed — would Titan be enshrouded within a warm, atmospheric greenhouse or possess a thin, cold atmosphere with a warm layer at high altitudes? The reddish appearance of Titan's atmosphere led scientists to suggest that atmospheric chemistry driven by ultraviolet sunlight and / or the interaction with Saturn's magnetospheric plasma produced organic molecules. The term "organic" refers here to carbon-based compounds, not necessarily of biological origin.

Later, laboratory experiments and theoretical research were aimed at reproducing the appearance of Titan's spectrum and learning if Titan's atmosphere could indeed be considered a prebiological analog to Earth's atmosphere. Researchers filled laboratory flasks with various mixtures of gases, including methane, and exposed the flasks to ultraviolet radiation. The experiments produced dark, orange–brownish polymers dubbed "tholins," from the Greek word meaning "muddy."

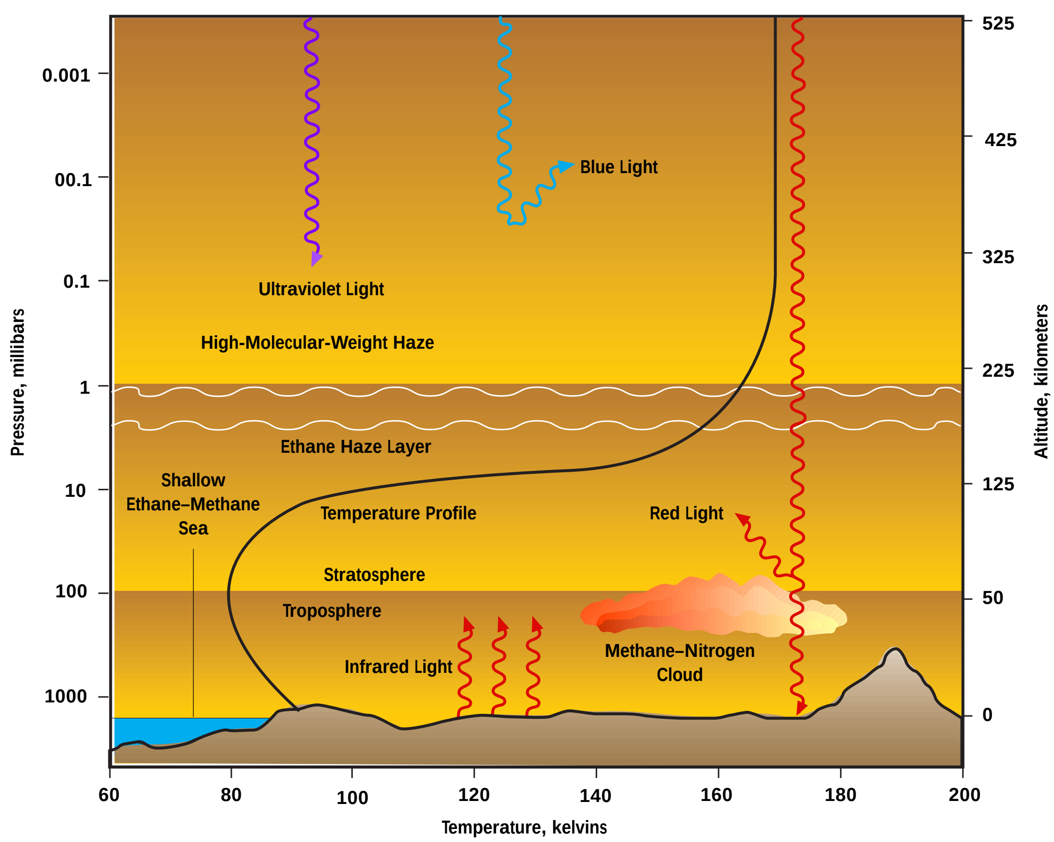
Voyager Results. In 1980 and 1981, the Voyager spacecraft flybys returned a wealth of data about Titan. Voyager 1 skimmed by at a distance of just 4000 kilometers. Voyager images revealed an opaque atmosphere with thin, high hazes. There was a significant difference in brightness between the northern and southern hemispheres and polar hoods, attributed to seasonal variations.

Voyager's solar and Earth occultation data, acquired as the spacecraft passed through Titan's shadow, revealed that the dominant atmospheric constituent is nitrogen. Methane, the atmospheric gas detected from Earth, represents several percent of the composition of the atmosphere. Titan's surface pressure, one and a half bars, is 50 percent greater than Earth's — in spite of Titan's smaller size. The surface temperature was found to be 94 kelvins, indicating that there is little greenhouse warming. The temperature profile in Titan's atmosphere has a shape similar to that of Earth: warmer at the surface, cooling with increasing altitude up to the tropopause at 42 kilometers (70 kelvins), then increasing again in the stratosphere.

The opacity of Titan's atmosphere turned out to be caused by photochemical smog: Voyager's infrared spectrometer detected many minor constituents generated primarily by photochemistry of methane, which produces hydrocarbons such as ethane, acetylene, and propane. Methane also interacts with nitrogen atoms created by the break up of nitrogen to form "nitriles" such as hydrogen cyanide. Titan may well deserve the title "smoggiest world in the solar system."

A person standing on Titan's surface in the daytime would experience a level of daylight equivalent to perhaps 1/1000 the daylight at Earth's surface, given Titan's greater distance from the Sun and the haze and gases blocking the Sun. The light will still be 350 times brighter than moonlight on an Earth night with a full Moon.

In the years following the Voyager mission, a stellar occultation observed from Earth in 1989 provided more data at a Titan season different from the season that Voyager observed. Extensive theoretical and laboratory experiments have also increased our understanding of Titan's complex atmosphere. For instance, this work has helped us to understand complex atmospheric photochemistry and the composition of the haze particles.



The change in Titan's temperature with altitude is like Earth's: decreasing with increasing altitude up to 50 kilometers, then increasing again above that. This illustration shows atmospheric structure, the location of the surface-obscuring ethane haze and the possible location of clouds.

CONSTITUENTS OF THE TITAN ATMOSPHERE

Chemical Constituent	Common Name	Atmospheric Concentration
N_2	Nitrogen	90–97 percent
Hydrocarbons		
CH_4	Methane	2–10 percent
C_2H_2	Acetylene	2.2 parts per million
C_2H_4	Ethylene	0.1 parts per million
C_2H_6	Ethane	13 parts per million
C_3H_8	Propane	0.7 parts per million
Nitriles		
HCN	Hydrogen cyanide	160 parts per billion
HC_3N	Cyanoacetylene	1.5 parts per billion

To summarize, prior to Cassini, the primary constituents of Titan's atmosphere have been detected, the process by which photolysis of methane has produced a smoggy haze is fairly well understood and the pressure–temperature profile as a function of altitude in the atmosphere has been determined. We do not know the source of the atmosphere, if there is active "weather" (clouds, rain, lightning) nor how the atmosphere circulates. These are the intriguing science questions the Cassini Orbiter and the Huygens Probe will soon investigate.

Atmospheric Origin and Chemistry. What is the source of molecular nitrogen, the primary constituent of Titan's current atmosphere? Is it primordial (accumulated as Titan formed) or was it originally accreted as ammonia, which subsequently broke down to form nitrogen and hydrogen? Or did the nitrogen come from comets? These important questions can be investigated by looking for argon in Titan's atmosphere.

Both argon and nitrogen condense at similar temperatures. If nitrogen from the solar nebula — out of which our solar system formed — was the source of nitrogen on Titan, the ratio of argon to nitrogen in the solar nebula should be preserved on Titan. Such a finding would mean that we have truly found a sample of the "original" planetary atmospheres. Argon is difficult to detect, however, because it is a noble gas — it was not detectable by Voyager instrumentation. The upper limit that has been set observationally is one percent relative to nitrogen; the solar nebula ratio is close to six percent.

Methane is the source of the many other hydrocarbons detected in Titan's atmosphere. It breaks down in sunlight into fragments such as CH_2 and H_2. The CH_2 fragments recombine to produce hydrocarbons. Ethane is the most abundant by-product of the photochemical destruction of methane. The leftover hydrogen escapes from Titan's atmosphere. This is an irreversible process, and the current quantity of methane in Titan's atmosphere — if not replaced — will be exhausted in 10 million years.

The hydrocarbons spend time as the aerosol haze in Titan's atmosphere obscuring the surface. Polymerization can occur at this stage, especially for hydrogen cyanide and acetylene, forming additional aerosols that eventually drift to the surface. Theoretically, the aerosols should accumulate on the surface, and, over the life of the solar system, produce a global ocean of ethane, acetylene, propane and so on, with an average depth of up to one kilometer. A large amount of liquid methane mixed with ethane could theoretically provide an ongoing source of methane in the atmosphere, analogous to the way the oceans on Earth supply water to the atmosphere. Radar and near-infrared data obtained from Earth-based observations show, however, that there is no global liquid ocean, although there could be lakes and seas, or possibly subsurface reservoirs. The ultimate fate of Titan's hydrocarbons, which are expected to exist as liquids or solids on its surface, is a mystery.

Titan has been described as having an environment similar to that of Earth before biological activity forever altered the composition of Earth's atmosphere. It is important to emphasize that a major difference on Titan is the absence of liquid water — absolutely crucial for the origin of life as we know it. Liquid water may occur for short periods after a large comet or meteoroid impact, leading perhaps to some interesting prebiotic chemistry. However, the surface temperatures at Titan are almost certainly cold enough to preclude any biological activity at Titan today.

Winds and Weather. Titan's methane may play a role analogous to that of water on Earth. Might we expect Titan to have methane clouds and rain? At this point, the data suggest otherwise. Voyager infrared data are "best fit" with an atmosphere that is supersaturated with methane. This means that the methane wants to form rain and snow but lacks the dust particles on which the methane could condense.

Titan appears to have winds. The temperature difference from the equator to 60 degrees latitude may be as much as 15 kelvins, which suggests that Titan might have jet streams similar to those in Earth's stratosphere. Wind speeds in Titan's stratosphere may reach 100 meters per second. The occultation of the star 28 Sgr observed from Earth in 1989 confirmed this theoretical analysis by detecting the shape of Titan's atmospheric bulge, which is influenced by high-altitude winds. In the troposphere, the temperature as a function of latitude varies by only a few degrees, and the atmosphere should be much calmer.

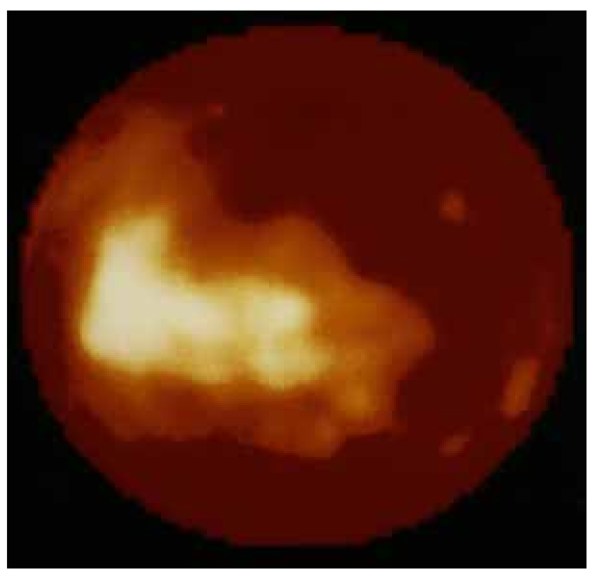
Titan's Surface

The surface of Titan was not visible through the limited spectral range of the Voyager cameras. Our knowledge of the surface of Titan comes from much more recent Earth-based images, acquired at longer wavelengths with the Wide Field and Planetary Camera aboard the Hubble Space Telescope. Brightness variations are evident, including a large, continent-size region on Titan's surface with a distinctly higher albedo (reflectance) at both visible and near-infrared wavelengths.

Preliminary studies suggest that a simple plateau or elevation difference on Titan's surface cannot explain the image features, and that the brightness differences must be partly due to a different composition and / or roughness of material. Like other moons in the outer solar system, Titan is expected to have a predominantly water-ice crust. Water at the temperatures in the outer solar system is as solid and strong as rock. Observations show weak spectral features indicative of ice on Titan's surface, but some dark substance is also present. This suggests that something on the surface is masking the water ice.

Surface Geology. At the resolution provided by the Hubble Space Telescope, we can establish Titan's rotation rate, and also agree that this moon has a continent-size albedo feature. The surfaces of solid bodies in the solar system have been altered primarily by three processes: impact cratering, volcanism and tectonics. Erosion may also be important on bodies with atmospheres. By studying the surface of a body, scientists can determine how it has evolved — when the surface solidified, the subsequent geological processes and how the surface and atmosphere interact.

Planetary geologists use crater statistics to determine the relative age of a surface. Since the population of im-



A composite of images of Titan's surface acquired in 1994 by the Hubble Space Telescope shows brightness variations, including a large region that appears bright at visible and near-infrared wavelengths. This region is also a good reflector of radar.

The processes of plate tectonics and erosion have erased the signature of all but the most recent of Earth's impact craters, such as the Meteor Crater in Arizona.

By contrast, in the case of Jupiter's moons, Callisto's cratered surface froze early in the history of the solar system, and has experienced only limited evolution since that time. Continuous volcanism gives Io (left) the youngest surface in the solar system.

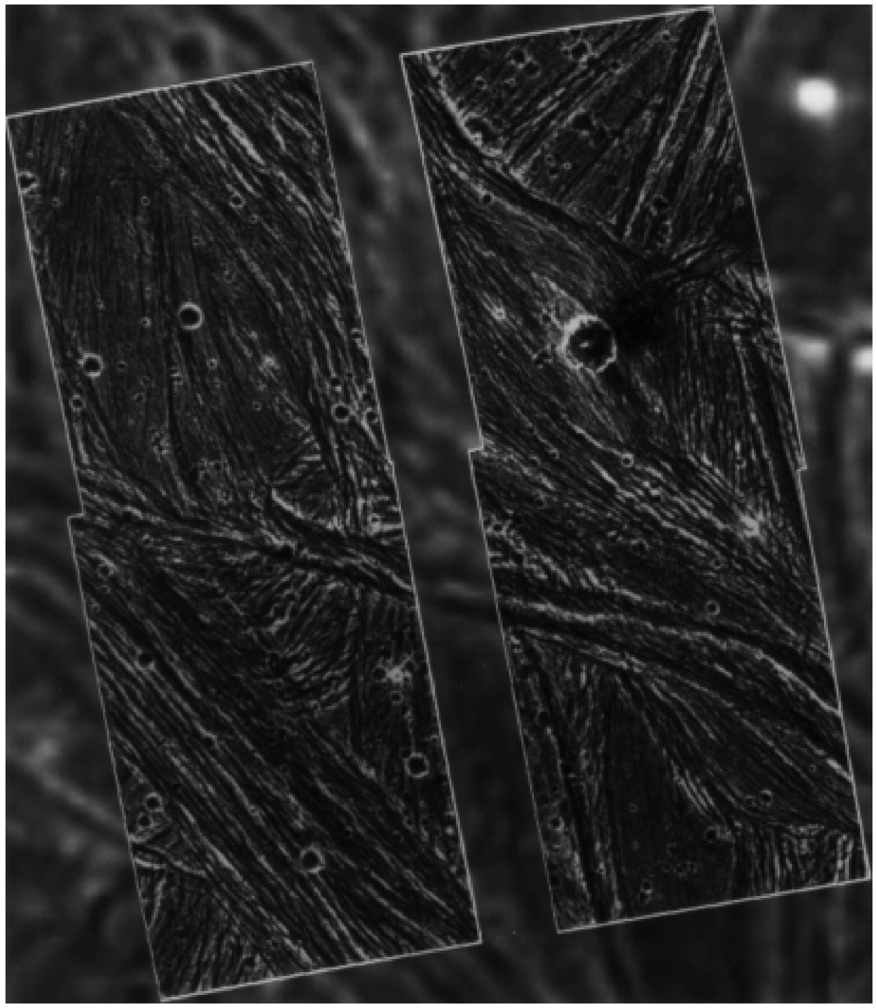
Jupiter's moon Ganymede is the only moon in the solar system larger than Titan. The two moons may have similar geology — with regions modified by ice tectonics, but a surface that basically solidified three to four billion years ago, now scarred by craters. This view of Ganymede shows a Galileo image superimposed on a much less detailed Voyager image.

pactors was greatest early in the history of the solar system, the more craters there are on a surface, the older the surface must be. Looking at a body like Jupiter's moon Callisto, covered with impact craters, it is clear that the surface is old and that the effect of geological processes has been minimal.

On Earth, tectonic forces and erosion have obliterated all old craters and erosion has modified the few recent ones. On a body like Io, another moon of Jupiter, active volcanism has covered all signs of craters, and the young landscape is dominated by volcanic features. At which end of this spectrum will we find Titan?

Earth-based radar data suggest a surface similar to that of Callisto. Titan's size alone suggests that it may have a surface similar to Jupiter's moon Ganymede — somewhat modified by ice tectonics, but substantially cratered and old. If Titan's tectonic activity is no more extensive than that of Ganymede, circular crater basins may provide storage for lakes of liquid hydrocarbons. Impactors create a layer of broken, porous surface materials, termed "regolith," which may extend to depths from one to three kilometers. The regolith could provide subsurface storage for liquid hydrocarbons as well.

In contrast to Ganymede, Titan may have incorporated as much as 15 percent ammonia as it formed in the colder, Saturn region of the solar nebula. As Titan's water-ice surface froze, ammonia–water liquid would have been forced below the surface. This liquid will be buoyant relative



to the surface water-ice crust; thus, ammonia–water magma may have forced its way along cracks to the surface, forming exotic surface features.

What amount of weathering of the surface might Cassini–Huygens see? On Earth, water accomplishes weathering because as it expands in its freeze–thaw cycle, rocks are broken up. In its liquid phase, water acts as the medium for many chemical reactions. On Titan, condensed hydrocarbons may or may not participate in a weathering process, but may also be expected to form a solid and / or liquid veneer over the icy surface.

The high-contrast features seen in the Hubble Space Telescope images are not consistent with a surface uniformly covered with liquid, suggesting some transport of the hydrocarbons into lakes or subsurface reservoirs.

Interior Structure

Titan's average density is 1.88 grams per cubic centimeter, suggesting a mixture of roughly 50 percent rocky silicate material and 50 percent water ice. Given the temperature and pressure of the solar nebula at Saturn's distance from the Sun when Titan was accreting, it is possible that methane and ammonia would have been mixed with the water ice. The formation of Titan by accretion was undoubtedly at temperatures warm enough for Titan to "differentiate," that is, for the rocky material to separate to form a dense core, with a water–ammonia–methane ice mantle.

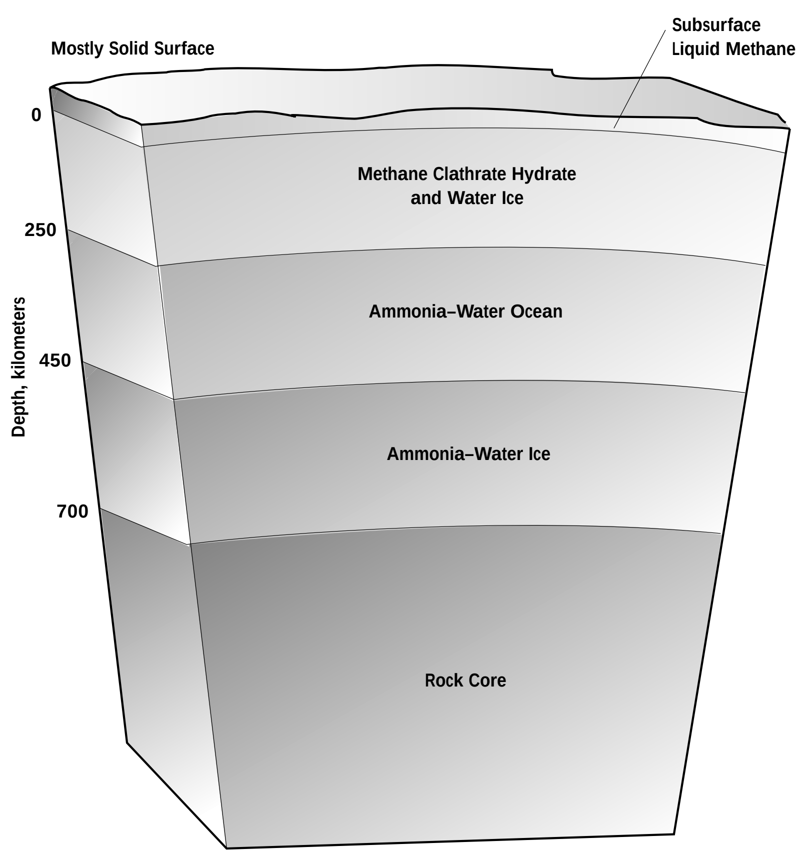
The mixture of ammonia with water could ensure that Titan's interior is still partially unsolidified, as the ammonia will effectively act like antifreeze. Radioactive decay in the rocky material in the silicate-rich core would heat the core and mantle for approximately three billion years, further strengthening the case that a liquid layer in the mantle could exist to the present. Titan's solid water-ice crust may be laced with methane clathrate — methane trapped in the structure of water ice. This could provide a possible long-term source for the methane in Titan's atmosphere — if the methane were freed by ongoing volcanism. An alternative model for providing the methane is a porous crust where the methane–water clathrate ratio is approximately 0.1.

Cassini–Huygens Experiments
On the first orbit after Cassini has executed its Saturn orbit insertion maneuver, the Huygens Probe will be targeted for Titan. Probe data are obtained during the descent through Titan's atmosphere and relayed to the Orbiter; then the Orbiter mission continues with over 40 more Titan flybys.

Magnetospheric Investigations. As the Orbiter encounters Titan, the science instruments will work together to investigate the fields and particles science associated with Titan and help determine if the satellite has an intrinsic magnetic field. The Cassini Plasma Spectrometer will map out the plasma flow. The Magnetospheric Imaging Instrument will measure high-energy particles and image the distribution of neutral particles surrounding Titan during the approach and departure of the Orbiter.

Through the measurement of plasma waves, the Radio and Plasma Wave Science instrument will investigate the interaction between the plasmas and high-energy particles, and will also search for radio emission associated with Titan. The Cosmic Dust Analyzer will map out the dust distribution. The Ion and Neutral Mass Spectrometer and the Cassini Plasma Spectrometer will measure the composition of Titan's atmosphere and exosphere directly during the flyby, to determine composition and study the interaction with Saturn's magnetosphere.

Atmospheric Investigations. The main purpose of the Huygens Probe is to return in situ measurements as it descends through Titan's atmosphere and lands on the surface. The Probe's



This model of Titan's interior envisions an underground ocean of liquid ammonia and water, 250 kilometers beneath the solid surface.

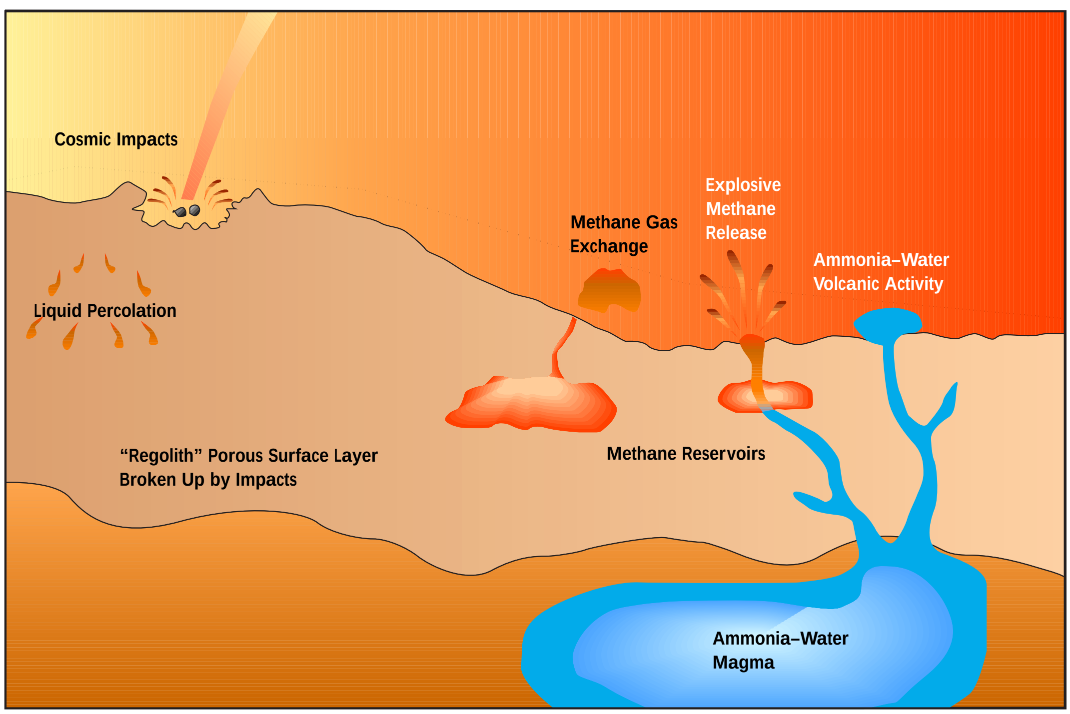
suite of instruments has been optimized for the return of information on critical atmospheric parameters. The atmospheric structure instrument will measure temperature, density and pressure over a range of altitudes, and also measure the electrical properties of the atmosphere and detect lightning.

The Aerosol Collector and Pyrolyser will vaporize aerosols, then direct the resulting gas to the Gas Chromatograph and Mass Spectrometer, which will provide a detailed inventory of the major and minor atmospheric species, including organic molecules and noble gases — in particular argon. The instrument for the Doppler Wind Experiment will track the course of the descending Probe, giving wind direction and speed at various altitudes in Titan's atmosphere. The Descent Imager and Spectral Radiometer will take pictures and record spectra of the clouds and surface. Measurements of the Sun's aureole collected by this instrument will help scientists deduce the physical properties of the aerosols (haze and cloud particles) in Titan's atmosphere. The instrument will also acquire spectra of the atmosphere at visible and near-infrared wavelengths and measure the solar energy deposited at each altitude level of the atmosphere.

The data acquired by the Probe will be compared with the continuing coverage provided by the Orbiter's subsequent flybys. The Orbiter's three spectrometers (the Ultraviolet Imaging Spectrograph, the Visible and Infrared Mapping Spectrometer and the Composite Infrared Spectrometer) will detect chemical species at a variety of levels in the atmosphere. By mapping the distribution of hydrocarbons as a function of time, the information from the spectrometers will address the sources, sinks and efficiency of the photochemical processes making up the hydrocarbon cycle. The Ultraviolet Imaging Spectrograph can also detect argon and establish Titan's deuterium–hydrogen ratio.

The Orbiter will study the circulation of Titan's atmosphere using the Visible and Infrared Mapping Spectrometer and the Imaging Science Subsystem's cameras to track clouds. For the study of Titan's weather, scientists will combine data from the Orbiter's Composite Infrared Spectrometer and the Radio Science Instrument experiments to develop temperature profiles and thermal maps.

Titan's subsurface structure may be key to understanding the properties of its surface. Photochemical models of Titan's atmosphere predict the existence of a global ocean of liquid ethane and methane, acetylene and other hydrocarbon precipitates — while Earth-based radar data and near-infrared images suggest a solid surface. If Titan's crust is sufficiently porous, storage space could exist for large quantities of liquid hydrocarbons, which would not show up in the radar data. The porous regolith produced by impacts could be over one kilometer thick, providing sufficient volume to hide the expected hydrocarbons.



Surface Science. The highest resolution, clearest images of Titan's surface will come from the Descent Imager and Spectral Radiometer on the Huygens Probe. This camera will take over 500 images under the haze layer — where the atmosphere may be very clear — during the Probe's journey to the surface.

If the Probe survives a landing on liquid, aerosol drifts or ice, chemical samples may be analyzed using the gas chemical analyzer. The camera will image the surface, while information on the atmosphere will be relayed by the Huygens Atmospheric Structure Instrument and Doppler Wind Experiment instrument. The Probe's surface science instrumentation will measure deceleration upon impact, test for liquid surface (if waves are present, the instrument can detect the bobbing motion) or fluffy surface and conduct investigations of liquid density, optical refractivity and thermal and electrical properties.

The Cassini Orbiter instruments have the capability to penetrate the hazy atmosphere for data gathering. The Orbiter's radar can map the surface through the clouds with high-resolution swaths in a manner similar to the Magellan mission's mapping of Venus' cloud-enshrouded surface. The radar will provide data on the extent of liquid versus dry land and map surface features at high resolution (hundreds of meters) in narrow swaths.

The Orbiter's camera and visible and infrared radiometer can provide global coverage by imaging through long-wavelength "windows," where atmospheric aerosols do not block sunlight. The combined set of data from these instruments will allow scientists to determine the dominant geological processes — cratering, volcanism and erosion. Titan's spin vector and reference features for making maps will be established, and data from the radar altimeter will provide estimates of the relative elevations. If large bodies of liquid exist, winds may be detected through measurements of the surface roughness.

Interior Structure. Titan's interior structure can be determined indirectly. As it passes close to Titan, the Cassini Orbiter's path will be altered by the

Artist's conception of the Huygens Probe descending through Titan's atmosphere.

This artist's rendering illustrates the Cassini Orbiter's radar as it maps swaths of Titan's surface.

satellite's gravitational field. The resulting change in the Orbiter's velocity will be detected on Earth as a Doppler shift in the spacecraft's radio signal. Understanding the basic structure of Titan's gravitational field allows scientists to determine the satellite's moment of inertia, thereby establishing whether Titan has a differentiated core and layered mantle.

Titan's eccentric orbit carries it to varying distances from Saturn. As Titan gets nearer and farther from Saturn, the shape of the satellite changes due to tidal forces. This may cause a detectable change in Titan's gravitational field that can be measured by flying close to Titan a number of times when the satellite is at different locations in its orbit. Such deformation is a measure of the rigidity of Titan, as it flexes because of tidal forces, which can then be used to infer whether or not it has a liquid layer in the mantle.

A World of Its Own

The interaction between Titan's atmosphere and magnetosphere is very complex and many questions still remain. Most of the progress to date has been made using Voyager 1 results, combined with computer modeling. Questions concerning precise interaction, such as the importance of ionization, neutral particle escape, shape of the Titan wake and how the interaction varies over the Titan orbit could all soon be answered by the Cassini–Huygens mission.

With over 40 flybys planned, the Cassini Orbiter should be able to answer the question of whether or not Titan has a significant internal magnetic field.

Understanding Titan's methane–hydrocarbon cycle is a major goal for Cassini–Huygens. Investigating the circulation of the atmosphere and the transport of these hydrocarbons is important to understanding Titan's climate and weather in many time domains: over days, over seasons and over the age of the solar system. The source of atmospheric methane is an intriguing puzzle — methane in Titan's atmosphere will be depleted by irreversible photolysis in less than 10 million years, so there needs to be a replenishing source of methane at or near the surface.

Titan presents an environment that appears to be unique in the solar system, with a thick, hazy atmosphere; a possible ocean of hydrocarbons; and a surface coated with precipitates from the atmosphere — similar to the scenario that scientists believe led to the origin of life on Earth. In the three centuries since the discovery of Titan, we have come to see it as a world strangely similar to our own — yet located about one and a half billion kilometers from the Sun.

When the Cassini Orbiter and Huygens Probe arrive at Titan, they will provide us with our first close-up view of Saturn's largest satellite. With the Probe's slow descent through Titan's atmosphere — with images of the surface and chemical composition data — and the Orbiter's radar maps of the moon's surface, we will once again be shown another world.